JOURNAL OF MATERIALS RESEARCH AND TECHNOLOGY 2023;25:2989–3006

Available online at www.sciencedirect.com

jmr&t Journal of Materials Research and Technology

journal homepage: www.elsevier.com/locate/jmrt

Performance investigation of cryogenic treated-double tempered cutting inserts in dry turning of Ti–6Al–4V alloy

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ARTICLE INFO

Article history:
Received 14 April 2023
Accepted 15 June 2023
Available online 20 June 2023

Keywords:
Ti–6Al–4V alloy
Turning
Carbide insert
KC5010
Cryogenic treatment
Tempering
Tool wear
Chip morphology

ABSTRACT

Dry machining of Titanium alloy Grade 5 (Ti–6Al–4V) with cryogenic treated, double-tempered KC5010 cutting inserts was examined. The impact of cryogenic treatment followed by tempering of the carbide inserts was investigated using microstructure analyses. The effects of constant depth of cut, cutting speed, and feed rate on machining variables (torque, force, surface roughness, temperature, and tool wear) were investigated. According to the experimental results, the cutting speed is the most important parameter that has a direct influence on the machining characteristics. Increased cutting speed and feed rate generate larger tangential pressures, allowing for a reduction in chip contact length; a shorter contact length results in reduced surface roughness and flank wear rate, respectively. The effects of cutting speed and feed rate on chip thickness were studied. Image analysis of the segmented chip was used to investigate the form and size of the saw-tooth profile of serrated chips. It was discovered that raising the cutting speed from 73 m/min to 160 m/min enhanced the free surface lamella of the chips and improved the visibility of the saw tooth segment. As cutting speed increases, all response parameters (torque, temperature, force, tool wear, and surface roughness) increase at the same time, by nearly 300%. Deep cryogenic treatment enhanced micro-hardness, resistance to wear, and toughness. As a result, there was reduced flank wear with tiny abrasion lines. Lower cutting speeds and feed rates resulted in less rake surface wear. Finally, the current study's convergence

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https://doi.org/10.1016/j.jmrt.2023.06.165

with earlier research was presented, indicating strong agreement between the two examinations.

1. Introduction

Titanium alloys have a lower mass in terms of strength and are more resistant to high temperatures, making them excellent for aviation applications. Because of its extensive uses in the aerospace business, medical instrument manufacturing industry, automobile industry, petrol and power plant industry, sports industry, and chemical industry, this alloy's machining is in great demand [1–3]. Because of its excellent corrosion resistance, excellent strength-weight ratio, superior chemical resistance, reduced density, greater specific strength, and exceptional thermal stability, this alloy has found widespread application in a variety of industries. Titanium alloy is further prone to chemical interactions with material used in cutting tools during machining; moreover, a reduced thermal conductivity rate quickens this phenomenon by causing the temperature to rise.

Cutting tool wear has an impact on the completed workpiece. The biggest challenge with machining Ti alloys is temperature. Amended cutting tool metals and new age coated tools with different coatings can increase Ti-alloy measured results. The most important element influencing tool wear is machining force. Helical-type chips are often chosen in metal machining. In recent decades, the quest for ecologically friendly goods has also fueled the improvement of novel procedures for enhancing tool life without using any cutting fluids. Inserts manufactured using Tungsten carbide (WC) are generally employed in the majority of production sectors due to their distinct qualities such as high microhardness, excellent wear resistance, high compressive strength, and stable thermal structure. Heat treatments and surface coatings are two contemporary procedures used on inserts to improve their methodical qualities. Several studies have been piloted for the generation of single- and multilayer cutting tool coatings. The surface coating technique's principal drawbacks are the difficult design of the cutting instrument and the expense of coating deposition. To address coating deficiencies, extensive research was conducted using a variety of cost-effective heat treatment techniques. Cryogenics technology is an alternate way of increasing the life of various cutting tools employed in machining processes. It changes the microstructural properties of the cutting tool directly, refining its qualities. Furthermore, the alteration of metallurgical properties caused by cryogenic treatment improves tool toughness, resistance to wear, and fatigue. Importantly, this low-temperature treatment procedure is both environmentally friendly and cost effective for producers. Several research investigations have reported numerous background phenomena for the increased features of cryogenic treated instruments as a result of these distinctive attributes.

A lot of work has been done to enhance the machinability quality and tool life of cutting inserts, either by cryogenic treatment, tempering, or combining both. Dhal et al. [1] analysed different machining aspects of titanium alloy grade 5 and stated the superiority of a cryogenic environment for achieving precision turning. Chinnasamy et al. [2] explored the performance of cryo-treated cutting inserts, suggesting that surface quality and tool life might be greatly enhanced by regulated cryogenic treatment at low temperatures. Sivaiah and Chakradhar [3] studied the turning of precipitated hardened stainless steel with a KC5010 insert under cryogenic chilling and optimised the parameters using the RSM approach. They identified feed rate as the most significant parameter for influencing surface roughness. Kara et al. [4,5] studied the hard turning of AISI D2 steel by employing several coated and uncoated cryogenically treated ceramic cutting tools and found that the coated tool outperformed the uncoated tool in terms of turning properties. Cryogenic showers, according to Chaharsooghi [6], can greatly increase the machinability of Ti–6Al–4V by achieving better material removal rates, lower tool wear, and improved surface characteristics. Sharma et al. [7] reported the results obtained in turning Ti–6Al–4V in different cutting environments and using different cutting tools. They reported cryogenic cooling along with a carbide insert as the most eco-friendly combination for turning titanium alloy grade 5 [8]. Bukane et al. [9] observed that PVD coated cutting inserts are excellent when turning any tougher alloy because they wear less and have better machining characteristics. Çiçek et al. [4] demonstrated that multilayered coated & cryogenic-treated HSS tools improved tool steel milling properties in dry and wet conditions, respectively. Mallick et al. [10] reported that CVD-coated KC5010 cutting inserts have a higher tool life as compared to PVD-coated inserts while turning harder alloys. Akgün and Kara [11] reported feed rate as the most influential parameter while dry turning AA6061-T6 alloy using a PVD coated KC5010 cutting insert and optimising using the Taguchi technique. Amrita et al. [12] reported the superiority of a graphene-filled cutting insert (KC5010) that provided better results in a MQL environment as compared to a dry insert through Inconel 718 alloy turning. Pradhan et al. [14–16] used a PVD coated cutting insert (KC5010) for turning Ti–6Al–4V alloy and optimised it using various optimisation techniques. They reported significant influential parameters that aided in machineability improvement. They obtained comparable results while working on Ti–6Al–4V alloy with the KC313 cutting insert [17,18]. They also verified the results using FEA [19]. Pradhan et al. [20] used a micro-grooved cutting insert (KC5010) for turning titanium alloy grade 2 and optimised it using WASPAS techniques. They discovered that micro-texturing with solid-lubricant cutting inserts is the most important constraint influencing machinability throughout machining. They reported feed rate as the most influential parameter while turning Al/SiCp-reinforced metal matrix composites using a KC5010 cutting insert and optimising using desirability function analysis [21].

Bagal et al. [22] used several optimisation strategies to optimise the roughness, wear, and force through dry turning of titanium alloy grade 5 by means of cryogenic treated and doubly tempered KC5010 cutting inserts, and the depth of cut was regarded as the most relevant parameter. According to Soppa and Pradhan [23], utilising cryogenic microtexturing cutting inserts improves cutting performance by enhancing tool life and surface smoothness. Sharma et al. [24,25] obtained a similar outcome. They confirmed the results by simulating the turning process of titanium alloy grade 2 via deform 3D for various coatings over the KC5010 insert [26]. Maity and Pradhan [27,28] machined titanium grade 5 alloy with a cryogenic treated KC5010 cutting insert under various lubricating conditions, reporting superior surface polish and lower tool wear with mist lubrication. They used several optimisation approaches and discovered that the most important parameter for managing roughness and flank wear was the depth of cut [29,30]. Finally, they investigated the behaviour of microgrooved cutting inserts using FEM modelling and discovered a 12% decrease in wear during turning of Ti–6Al–4V [31]. Deshpande et al. [32] investigated the enactment of an uncoated tungsten carbide cutting insert for turning Inconel 718 in both untreated and cryo-treated circumstances. Cryo-treated cutting inserts were superior for regulating machining sound, roughness, vibration, and cutting force. They also found similar results while spinning Inconel 718 with a small quantity of lubricant [33]. In hard alloy turning, Singla et al. [34] proved the usefulness of cryogenic treatment of tool inserts in increasing tool life and enhancing machinability. Das et al. [35] used the RSM approach to investigate machinability during dry turning of AISI 4340 steel by employing Cermet carbide. They found that deep cryo-treated-tempered cermet inserts had higher machinability and decreased tool wear during dry turning. According to Kara et al. [36], when the cylindrical grinding operation of AISI 5140 steel was executed employing the Taguchi technique and cryogenic treatment for 30 h, improved roughness characteristics were achieved. Deepthi et al. [37] employed the taguchi approach to improve the cutting performance of coated cryo-treated carbide cutting inserts while converting white cast iron. They observed that tool tip temperature is more exaggerated by cutting speed. Furthermore, cryo-treated and tempered cutting inserts outperform non-treated and cryo-treated inserts in terms of wear resistance and tool life. Sreeramareddy et al. [38] found that machining a C45 steel workpiece with cryo-treated carbide inserts was superior to machining with untreated inserts due to a decreased cutting force and tool tip temperature. Mist lubrication improved the machinability of cryogenic and double-tempered tungsten carbide cutting inserts when turning hot-rolled annealed steel, according to Gill et al. [39]. When turning ASSAB 760 plain carbon steel at higher cutting speeds, Seah et al. [40] proved the advantage of cryo-treated and triple-tempered carbide cutting inserts over cold-treated and triple-tempered inserts. Yong et al. [41] got comparable results when turning ASSAB 760 plain carbon steel with cryo-treated and single-tempered cutting inserts. After being cryo-treated for 24 h, Varghese et al. [42] found that cryo-treated-tempered cemented carbide cutting inserts gave greater milling and tool life when machining annealed maraging steel MDN 250. Padmakumar et al. [43] demonstrated that cryo-treated and tempered cemented carbide cutting inserts outperformed other cutting inserts in obtaining a reduced wear rate and longer tool life while converting grey cast iron. Padmakumar and Dinakaran [44] found a similar pattern.

Most of the researchers have cryogenic treated the tungsten carbide cutting inserts to enhance their life. Some researchers have also tempered the cryo-treated cutting inserts for better microstructural properties and tool life. Very little investigation has been reported on the machining of harder alloys, e.g., titanium alloys. Also, comparative studies of the machining of titanium alloy using different types of coated or non-coated cutting inserts (also conditioned to be non-treated, cryo-treated, tempered, or a combination of cryo-treated and tempered) have been reported less. Hence, there is a scope of investigation for the machining of titanium alloys of higher grades using such conditioned tungsten carbide cutting inserts. The current study begins with a deep cryogenic treatment followed by double tempering of a KC5010 PVD AlTiN-coated carbide cutting insert. Micro-hardness and microstructural studies were performed on the treated cutting inserts. A turning operation was done on Titanium alloy Grade 5 (Ti–6Al–4V) using the treated cutting inserts to explore its machinability. The effects of machining parameters such as cutting speed and feed rate on responses such as torque, cutting force, temperature, surface roughness, and tool wear were examined. Finally, micrographic experiments were performed on tools and chips to explore the impact of cutting settings on tool wear, chip generation, and chip properties. In addition, the convergence of the current studies' results with the prior researchers' studies was compared and discussed.

2. Experimental methodology

2.1. *Treatment of cutting inserts*

In this study, the KC5010 cutting inserts were cryogenic treated before tempering. It is a sophisticated PVD AlTiN coating on an extremely deformation-resistant tungsten carbide substrate that allows for high-speed cutting. It also works well with toughened and short-chip materials. The cutting inserts are kept inside the cryogenic chamber for deep cryogenic treatment (Fig. 1). The inlet end of the insulated hose is linked to the liquid nitrogen tank, and the outlet end is linked to the chamber. The PID controller controls the flow rate of the liquid nitrogen. The decremental change in temperature relating to time is given to gradually attain the cryogenic temperature. In a similar way, after the soaking period is over, the temperature will gradually increase to reach room temperature. This reduces the chance of microcrack formation, which may occur in the cutting inserts due to the sudden temperature change from 27 °C to −193 °C. In this experiment, the increase and decrease temperature rates are considered to be 2.2 °C/min. After the cryogenic temperature is attained, the

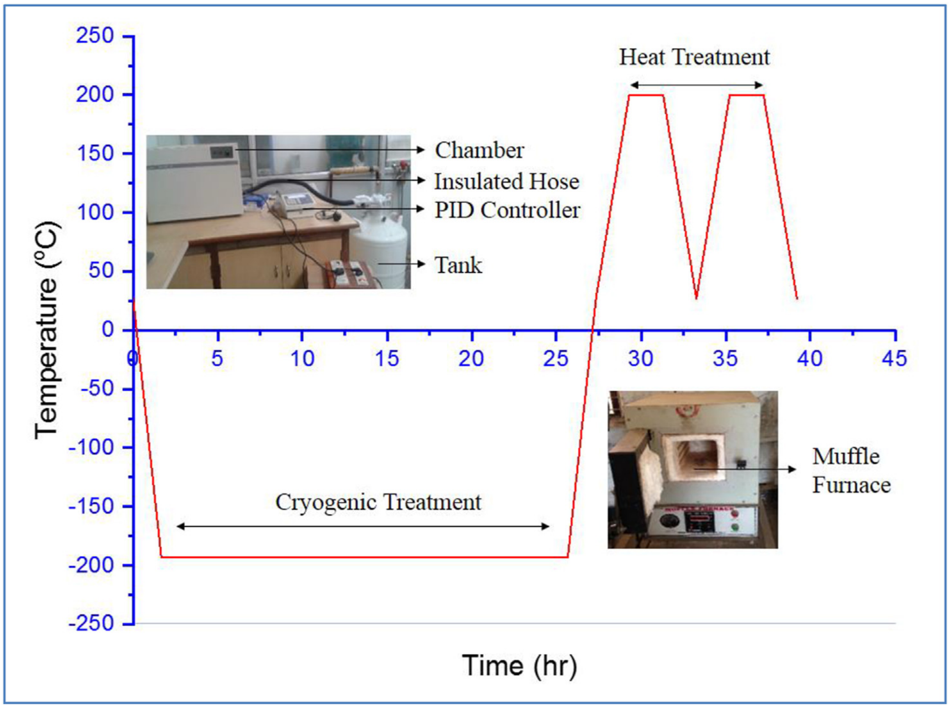

Fig. 1 – Cryogenic and double tempering of cutting inserts.

Fig. 2 – (a) Experimental setup; (b) Tool holder; (c) KC5010 cutting insert; (d) Ti–6Al–4V round bar [14].

Table 1 – Properties of Ti–6Al–4V.

Chemical properties		Mechanical properties	
Constituents	%	Property	Value
V	3.5–4.5	Elastic modulus	114 GPa
Al	5.5–6.76	Tensile strength	1000 MPa
O_2	<0.2	Thermal conductivity	7.2 W/mK
N_2	<0.05	Hardness, Rockwell	36 HRC
C	<0.08	Density	4.42 g/cm^3
Fe	<0.25		
Ti	Balance		

cutting inserts are kept at a relentless temperature of −193 °C for 24 h, which is also known as controlled cooling. Then again, the chamber temperature rises and is brought to room temperature. To reduce the induced stress formed in the cutting inserts due to cryogenic treatment, double tempering is carried out in the muffle furnace. In a similar manner, the temperature inside the furnace rises gradually at a rate of 2 °C/min and finally reaches 200 °C. The cutting insert was kept at the equivalent temperature for 2 h. After that, the temperature decreases to room temperature. The heating cycle is repeated again to complete the double tempering of the KC5010 cutting inserts.

2.2. *Machining setup*

Turning operation is carried out using Ti–6Al–4V as workpiece material with cryo-treated cutting inserts (Fig. 2). The experiment is performed in the precise lathe machine (Make: HMT Limited, Model: NH26). Round bar with a diameter of 50 mm and a length of 600 mm is utilised for the experiment [13]. The cutting inserts is Kennametal make with model number KC5010. Cryogenic treatment with double tempering is done in the cutting inserts to increase the micro-hardness while reducing the stress induced in it. Table 1 shows the chemical composition of the workpiece as well as its mechanical qualities.

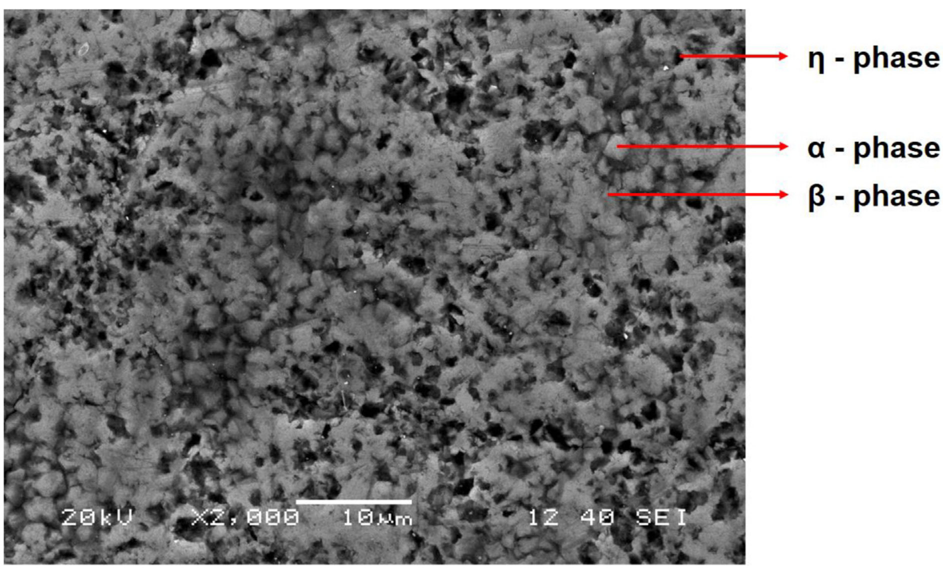

Fig. 3 – SEM micrograph of KC5010 cutting insert after cryo-double temper with α, β and η phase carbides.

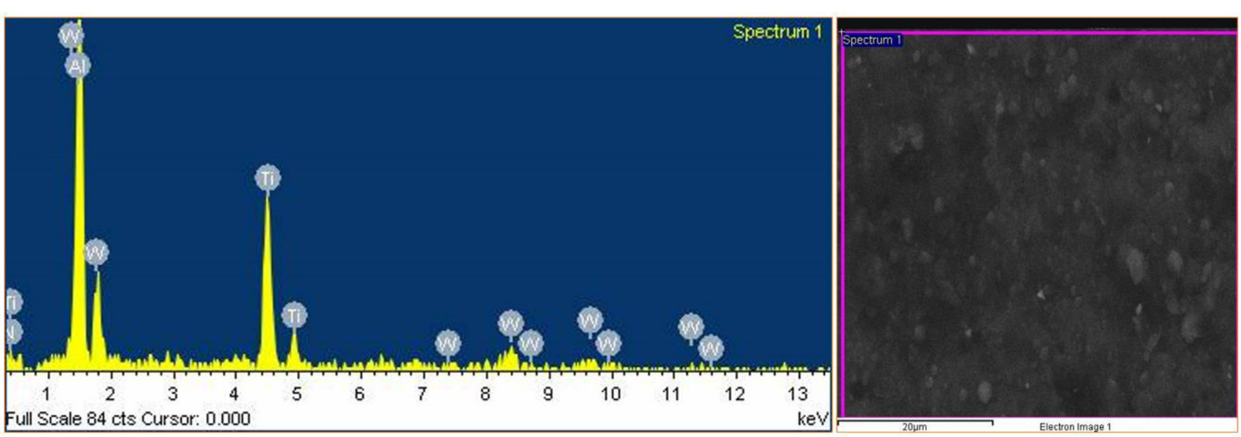

Fig. 4 – EDS of KC5010 cutting insert.

Table 2 – Vickers micro-hardness test results (MPa).

Insert Type	Measurement 1	Measurement 2	Mean
Untreated Cutting Insert	19168.08	19422.07	19295.07
Cryo-Treated Double Tempered Insert	19168.08	19422.07	19295.07

Table 3 – Cutting parameter with responses.

Sl. No.	Cutting Speed, m/min	Feed Rate, mm/rev	Depth of Cut, mm	Torque, Nm	Cutting Force, N	Temperature, °C	Surface Roughness, μm	Tool Wear, mm
1.	73	0.04	0.4	14.5	537	380	0.98	0.93
2.	95	0.04	0.4	15.7	485	295	0.91	0.98
3.	124	0.04	0.4	16.7	445	268	0.79	0.119
4.	160	0.04	0.4	18.2	340	256	0.68	0.243
5.	73	0.06	0.4	11.8	168	315	1.17	0.112
6.	95	0.06	0.4	11.5	185	328	1.12	0.169
7.	124	0.06	0.4	10.1	222	385	0.87	0.209
8.	160	0.06	0.4	10.3	265	400	0.78	0.375
9.	73	0.08	0.4	10.1	305	163	0.81	0.114
10.	95	0.08	0.4	13.2	318	181	1.45	0.254
11.	124	0.08	0.4	26.5	320	202	1.55	0.304
12.	160	0.08	0.4	45.1	645	262	1.91	1.692
13.	73	0.1	0.4	9.4	136	375	0.99	0.134
14.	95	0.1	0.4	10.5	200	380	1.5	0.143
15.	124	0.1	0.4	11.4	254	421	1.61	0.209
16.	160	0.1	0.4	27.3	420	487	1.62	0.707

The experiment is carried out by adjusting the process parameters, namely cutting speed and feed rate, while keeping the depth of cut constant, namely 0.4 mm. According to the machine specifications, the four levels of cutting speed are 73, 95, 124, and 160 M/min, with feed rate levels of 0.04, 0.06, 0.08, and 0.1 mm/rev. A total of 16 experimental runs are carried out by altering all levels of feed rate along with cutting speed. To evaluate cutting force, torque, surface roughness, cutting temperature, and flank wear, a piezoelectric tool dynamometer (Make: Kistler, Model: 9272), an infrared thermometer, a surface roughness tester (Make: Taylor Hobson, Model: Surtronic 3+), a tool maker microscope (Make: Mitutoyo, Model: TM-A505B), and an optical microscope (Make: Mitutoyo, Model: MF-UA1010D) are employed. The resulting serrated chips are examined under a scanning electron microscope (SEM) (Make: JEOL, Model: JSM-6084LV).

3. Results and discussions

3.1. *Microstructure analysis of insert*

Metallographic analysis was performed using microscopic observation in accordance with the ISO 4499–3:2016 regulation. The samples were grounded and polished in accordance with the standard. Murakami's Reagant was used to expose the grain structure on the polished surface for 5 s. A metallurgical microscope with a resolution of 2000X was used to examine the etched surface, revealing three primary microstructural phases: tungsten carbide (α-phase), cobalt (β-phase), and double carbide (η-phase). Fig. 3 shows SEM pictures of the cutting tool. The microstructure reveals that phase creates a consistent structure across the bulk material. The cryogenic treatment permanently releases micro tensions, extending the life of the cutting tool. The microscopic examination demonstrates that the carbide particle size and shape in treated inserts were evenly distributed and homogenous. It was also discovered that no - phase carbides were produced in either grade's cryogenic treated insert. The Energy-dispersive X-ray spectroscopy (EDS) investigation of the SEM image (Fig. 4(b)) is shown in Fig. 4(a) using Ultima IV XRD system.

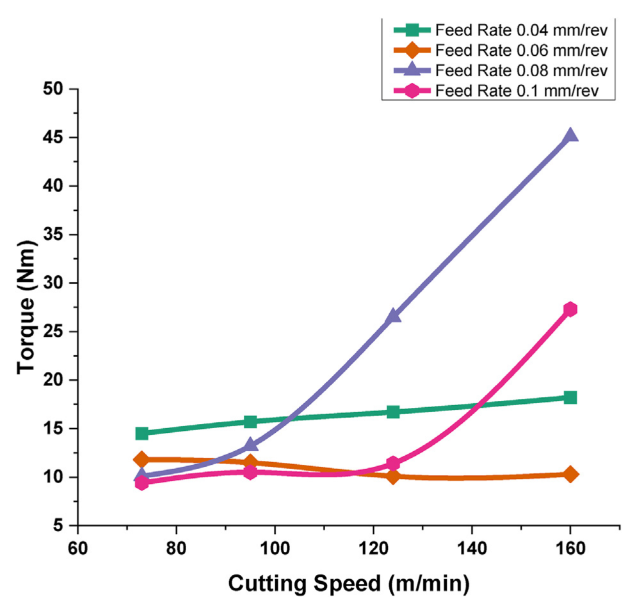

Fig. 5 – Cutting speed deviation with torque at different feed rate.

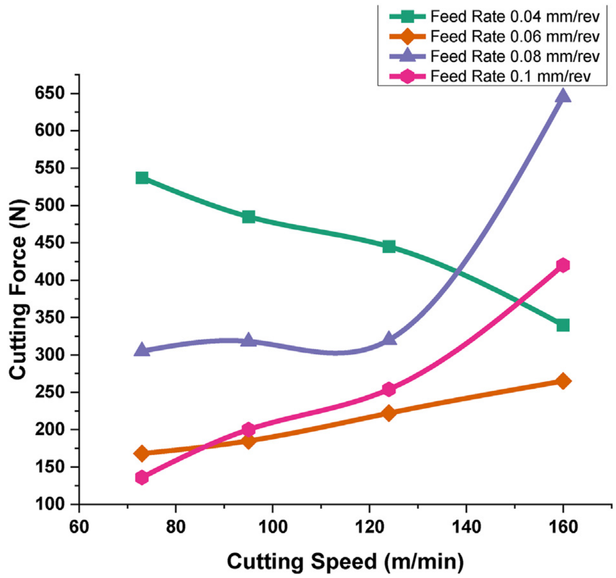

Fig. 6 – Cutting speed deviation with cutting force at different feed rate.

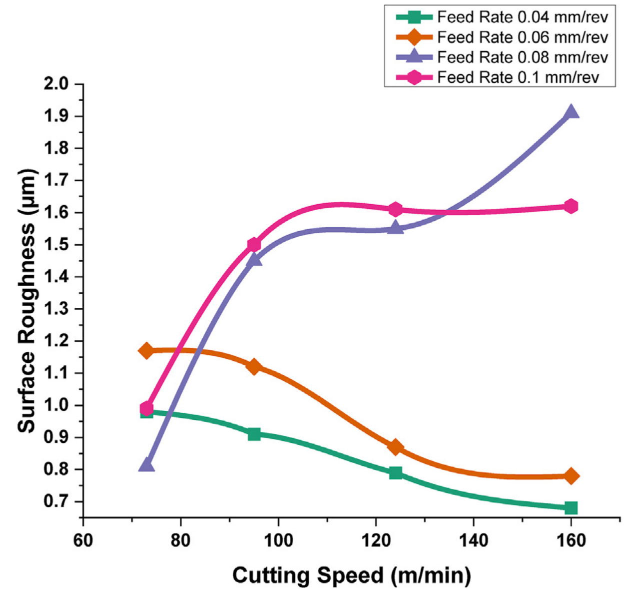

Fig. 8 – Cutting speed deviation with surface roughness at different feed rate.

The three phases are caused by a change in carbon percentage following cryogenic treatment, as seen by the EDX micrograph. The atomic percentage and weight of carbon increase after cryogenic treatment, whereas the grain size of inserts decreases. Conversely, tempering increases cobalt's atomic and weight % and decreases the carbon's atomic and weight % weight and atomic percentage decreased. Due to the phenomena of spheroidization, phase grain size refinement resulted in a more stable form. Due to tempering followed by cryogenic treatment, the hardness of cemented carbide inserts stays unaltered although it increases the micro hardness.

3.2. *Micro hardness*

The untreated and treated cemented carbide inserts were imperilled to a Vickers micro-hardness test in accordance with ISO 3878 using vicker hardness tester machine (Make: Mitutoyo, Model: HV-110). The load was set to 30 kg. The average value was utilised to evaluate both untreated and cryogenic treated and tempered inserts, as indicated in Table 2. According to Table 2, cryogenic treated and tempered inserts had a 6.2% higher HV30 micro-hardness than untreated inserts. This is because cryogenic treatment has a greater

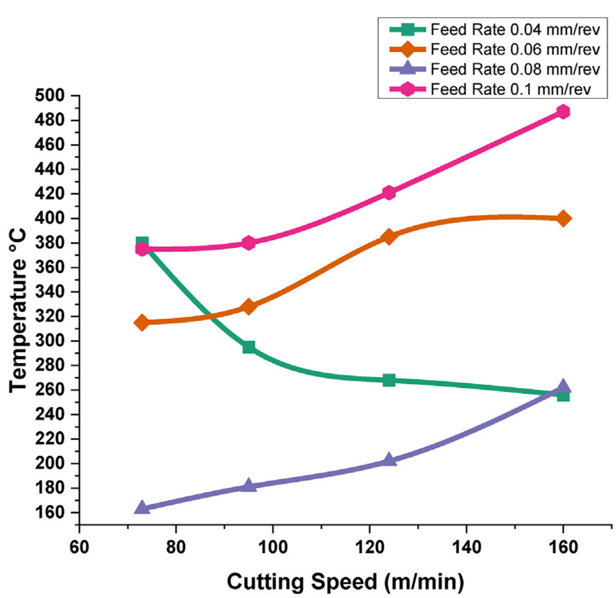

Fig. 7 – Cutting speed deviation with temperature at different feed rate.

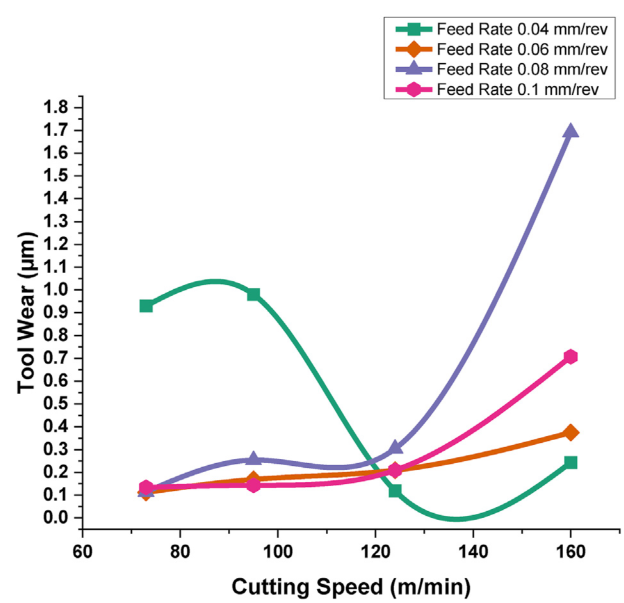

Fig. 9 – Cutting speed deviation with tool wear at different feed rate.

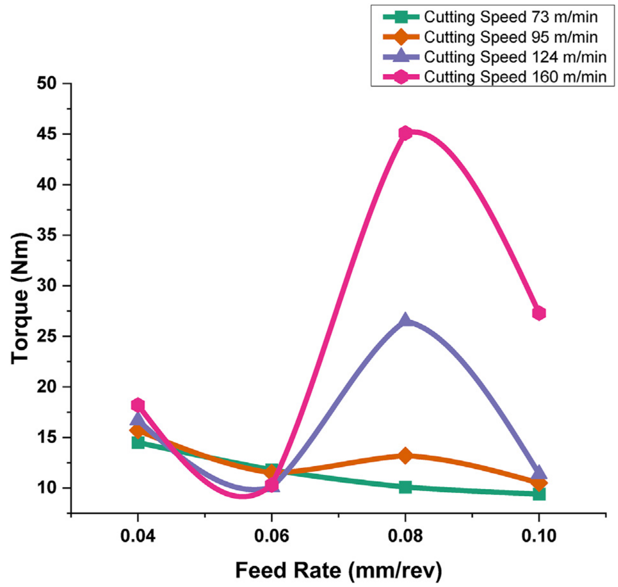

Fig. 10 – Feed rate deviation with torque at different cutting speed.

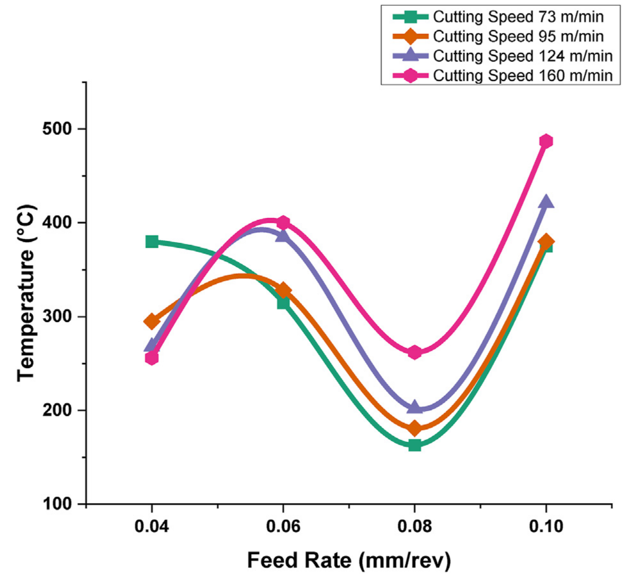

Fig. 12 – Feed rate deviation with temperature at different cutting speed.

influence on the metallic cobalt binder, increasing microhardness.

3.3. *Machining performance*

According to the design matrix, a dry turning operation of Ti6Al–4V with cryo-double-tempered cutting inserts was performed. Table 3 tabulates the cutting parameter design matrix as well as the recorded data from the outcomes. Torque, cutting force, temperature, tool wear, and surface roughness were all measured, as was the influence of feed rate and cutting speed on the responses.

3.4. *Effects of machining constraints on the responses*

3.4.1. *Effects of cutting speed*

Fig. 5 depicts the influence of cutting speed on torque at different feed rates. The torque increases as the cutting speed increases when the feed rates are 0.04 mm/rev, 0.08 mm/rev, and 0.1 mm/rev, but decreases when the feed rate is 0.06 mm/rev. A cutting speed of 73 m/min with a feed rate of 0.1 mm/rev produces the least torque, while a cutting speed of 160 m/min with a feed rate of 0.08 mm/rev produces the most torque. Fig. 6 depicts the impact of cutting speed on cutting force at various feed rates. The cutting force increases as the cutting speed increases when the feed rates are 0.06 mm/rev, 0.08

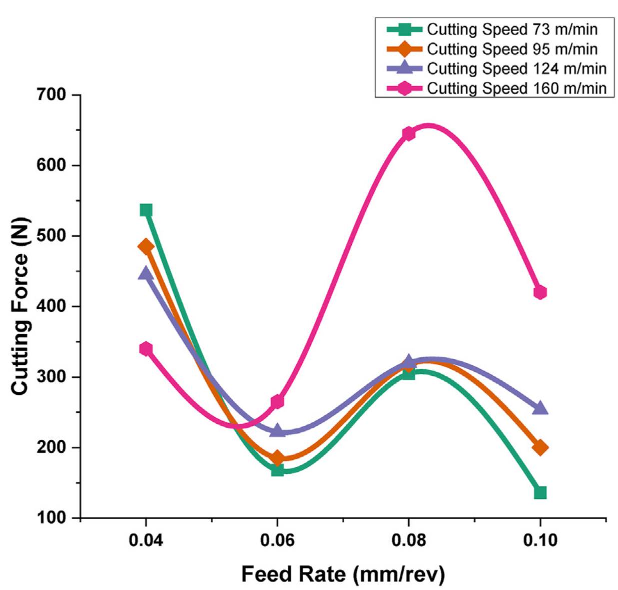

Fig. 11 – Feed rate deviation with cutting force at different cutting speed.

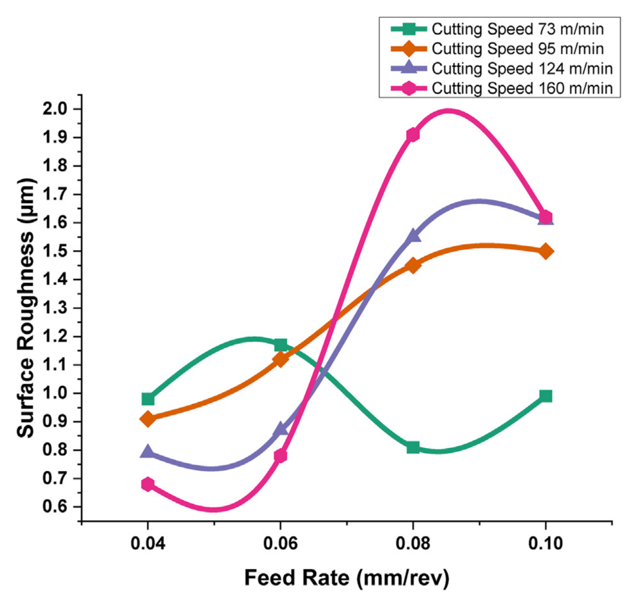

Fig. 13 – Feed rate deviation with surface roughness at different cutting speed.

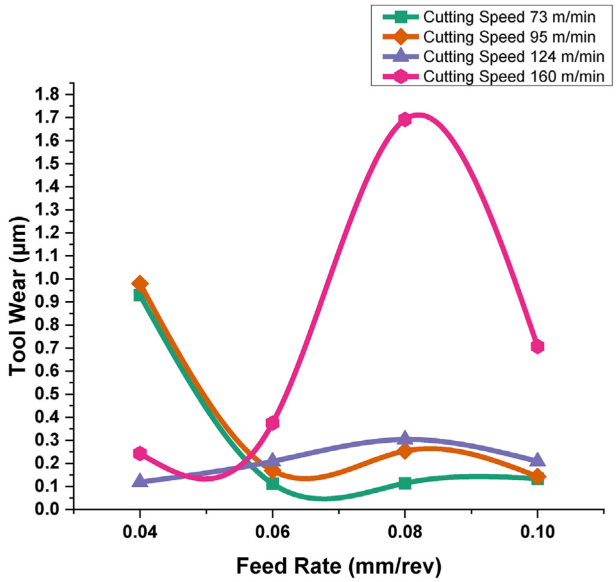

Fig. 14 – Feed rate deviation with tool wear at different cutting speed.

mm/rev, and 0.1 mm/rev, but falls when the feed rate is 0.04 mm/rev. The least cutting force is produced by cutting at 73 m/min with a feed rate of 0.1 mm/rev, while the maximum cutting force is produced by cutting at 160 m/min with a feed rate of 0.08 mm/rev. The influence of cutting speed on cutting temperature at varied input rates is shown in Fig. 7. The cutting temperature increases as the cutting speed increases when the feed rates are 0.06 mm/rev, 0.08 mm/rev, and 0.1 mm/rev, whereas it decreases when the feed rate is 0.04 mm/rev. The lowest cutting temperature is achieved at a cutting speed of 73 m/min and a feed rate of 0.1 mm/rev. The greatest cutting temperature is produced by a cutting speed of 160 m/min and a feed rate of 0.08 mm/rev. The influence of cutting speed on surface roughness at different feed rates is shown in Fig. 8. When the feed rate is between 0.08 mm/rev and 0.1 mm/rev, the surface roughness rises as the cutting speed increases. In the case of feed rates of 0.04 mm/rev and 0.06 mm/rev, surface roughness reduces as cutting speed increases. Surface roughness is lowest while cutting at 160 m/min with a feed rate of 0.04 mm/rev and greatest when cutting at 160 m/min with a feed rate of 0.08 mm/rev. Fig. 9 depicts the influence of cutting speed on tool wear at different feed rates. When the feed rate is 0.06 mm/rev, 0.08 mm/rev, or 0.1 mm/rev, the tool wear increases as the cutting speed increases. The least tool wear is produced by cutting at 124 m/min with a feed rate of 0.04 mm/rev, while the greatest is produced by cutting at 160 m/min with a feed rate of 0.08 mm/rev. A feed rate of 0.04 mm/rev provides considerable tool wear at lower cutting speeds and minimal tool wear at higher cutting speeds when compared to all other feed rates. This is due to the reduced friction of the low feed rate at high cutting speeds. As the cutting speed increases, there is a greater relative motion between the cutting tool and the workpiece. This leads to an

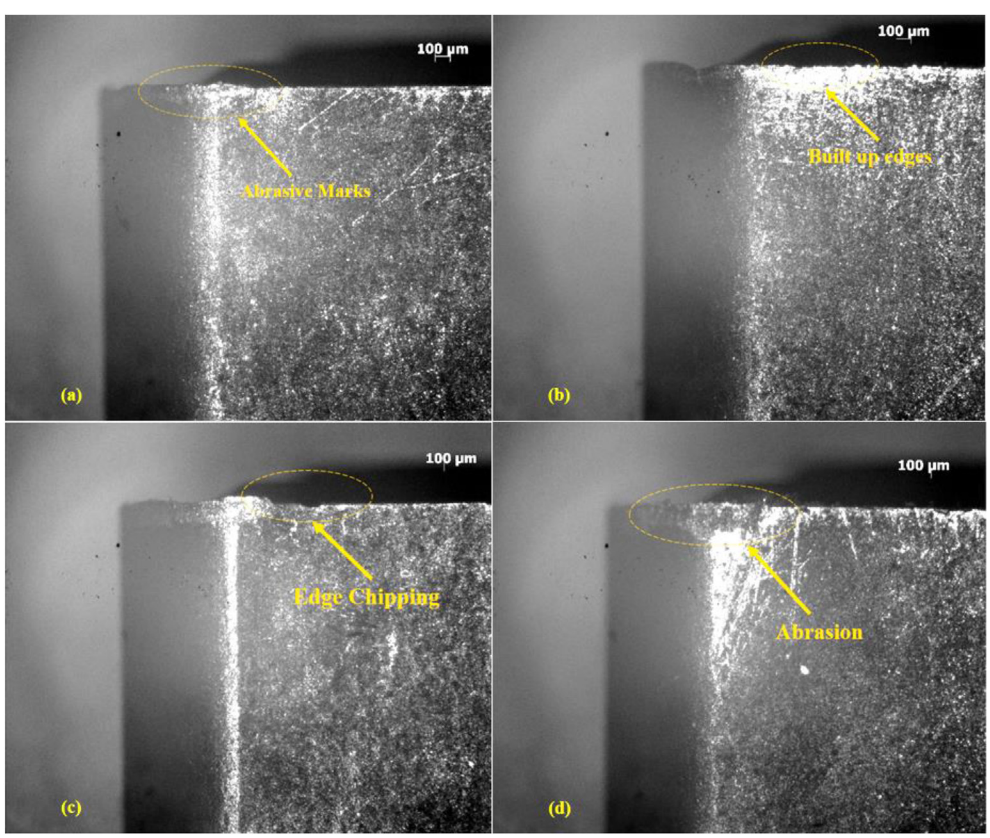

Fig. 15 – Toolmaker microscope images of treated cutting insert at feed rate of 0.04 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

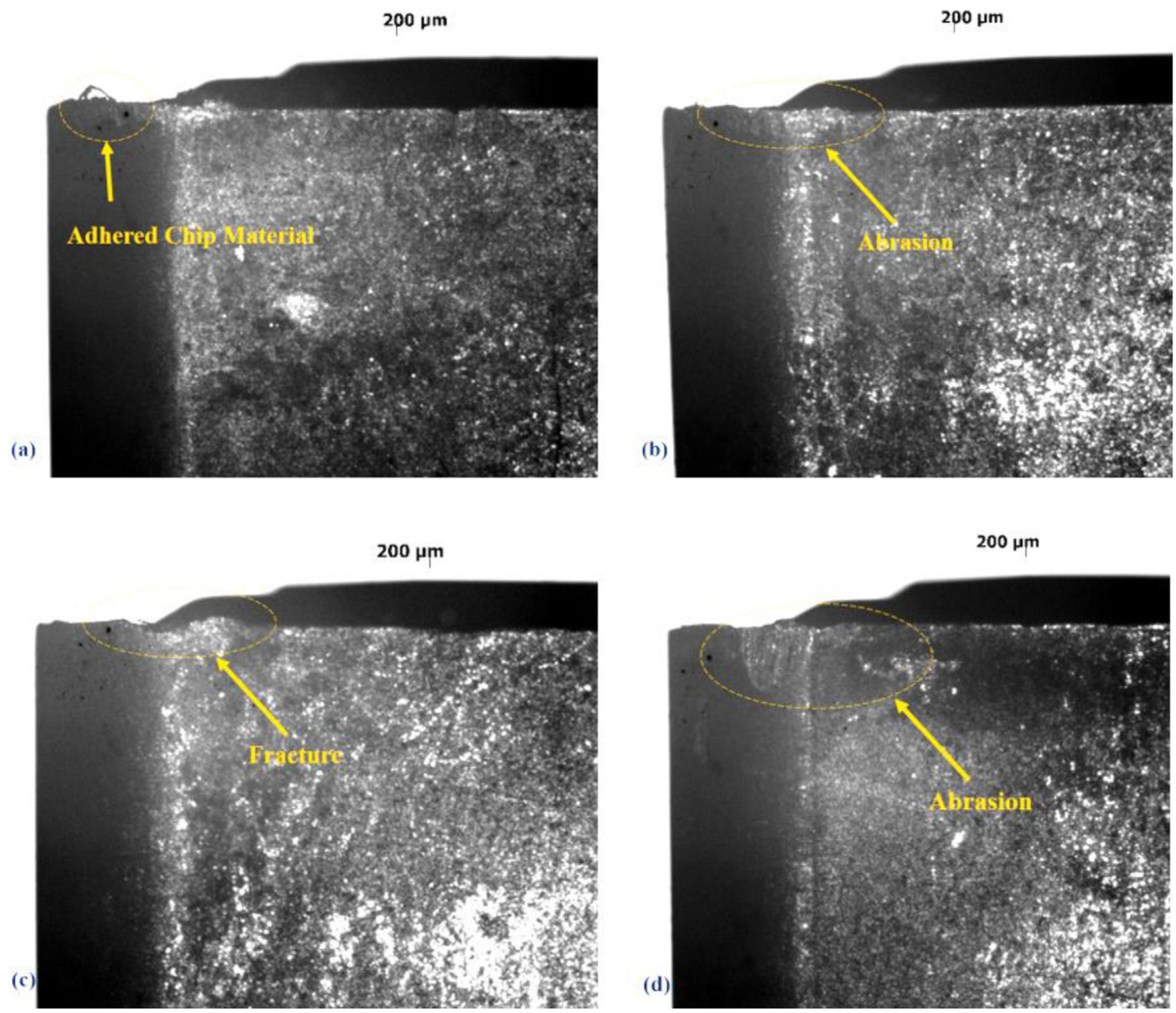

Fig. 16 – Toolmaker microscope images of treated cutting insert at feed rate of 0.06 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

increase in friction between the tool and the workpiece, resulting in higher cutting forces. The cutting forces are directly related to the amount of material being removed and the resistance encountered during the cutting process.

3.4.2. *Effect of feed rate*

Fig. 10 depicts the influence of feed rate on torque at different cutting speeds. At feed rates of 0.06 mm/rev and 0.08 mm/rev, respectively, cutting speeds of 160 m/min produce the lowest and greatest torque. Fig. 11 depicts the influence of cutting force on feed rate at various cutting speeds. At a feed rate of 0.04 mm/rev, a cutting speed of 73 m/min causes the lowest and greatest cutting forces. Furthermore, all other cutting speeds follow the same pattern as 73 m/min. Fig. 12 depicts the influence of cutting temperature on feed rate at various cutting speeds. Cutting at 73 m/min with a feed rate of 0.08 mm/rev generated the lowest temperature, while cutting at 160 m/min with a feed rate of 0.1 mm/rev produced the highest. Furthermore, all four cutting speeds follow the same pattern. The influence of feed rate on surface roughness at various cutting speeds is shown in Fig. 13. Cutting speeds of 160 m/min at feed rates of 0.06 mm/rev and 0.08 mm/rev resulted in the lowest and maximum temperatures, respectively. Fig. 14 depicts the influence of feed rate on tool wear at different cutting speeds. Cutting at 73 m/min with a feed rate of 0.06 mm/rev generated the least tool wear, while cutting at 160 m/min with a feed rate of 0.08 mm/rev produced the most. As the feed rate increases, there is more contact between the cutting tool and the workpiece. This increased contact leads to greater frictional forces, resulting in higher heat generation at the cutting interface. The temperature of the cutting zone rises due to this heat, leading to an increase in cutting temperature. The increase in cutting force and temperature can also negatively affect the tool itself. Higher cutting forces put additional stress on the tool, which can lead to faster tool wear, chipping, or even breakage. Elevated cutting temperatures can cause thermal damage to the cutting edge, reducing tool life and performance. Higher feed rates result in increased cutting forces acting on the tool and workpiece. These forces can cause more intense interactions between the tool and the

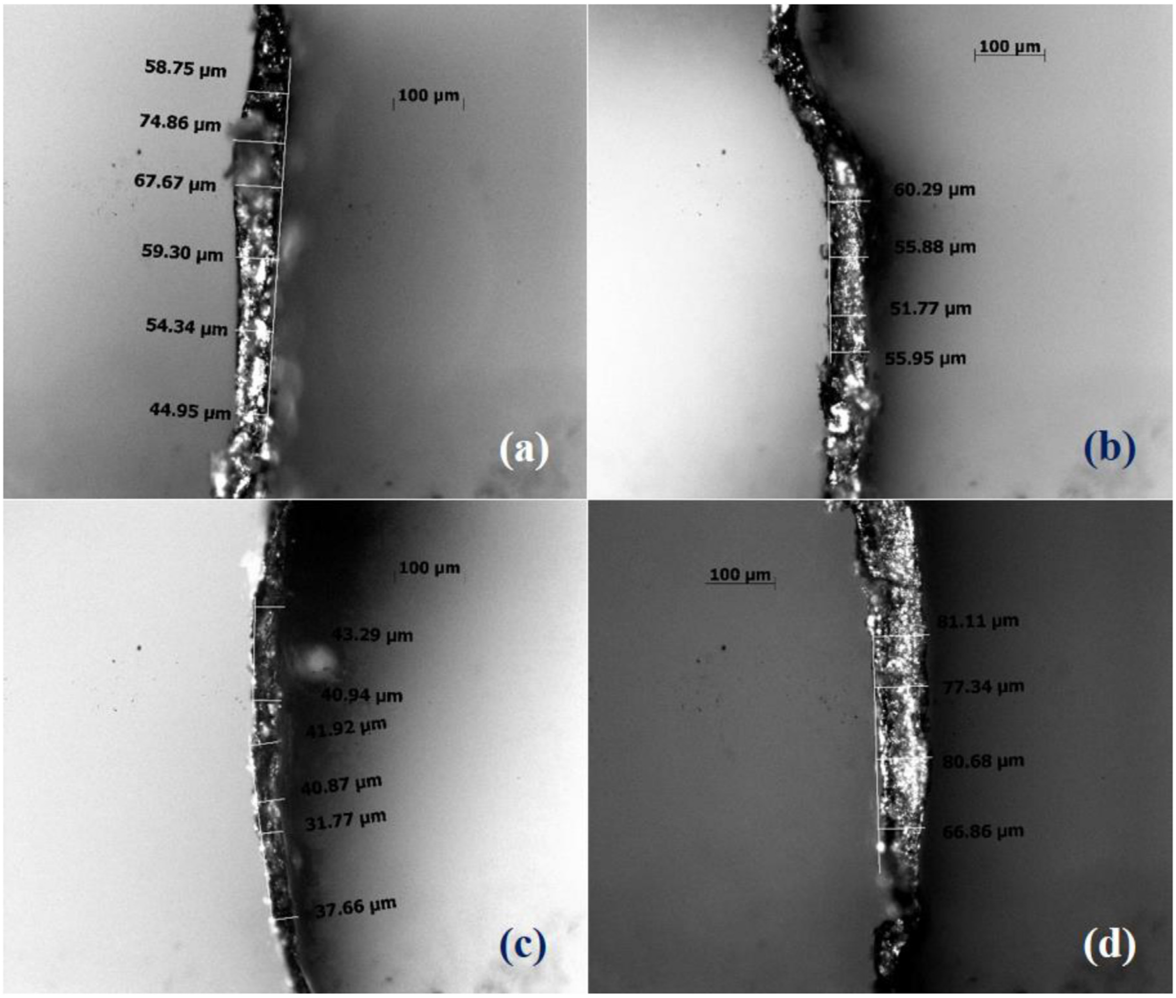

Fig. 17 – Chip thickness obtained during machining using treated cutting insert at feed rate of 0.04 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

workpiece, leading to higher tool wear. Additionally, the increased cutting forces can induce vibrations, which further exacerbate the tool wear and result in an uneven surface finish. Higher feed rates generally reduce the tool life due to the increased wear on the cutting edges. As the tool continues to cut at a faster rate, it experiences more contact with the workpiece material, leading to faster tool degradation and wear. Worn-out or damaged cutting edges can produce a rougher surface finish.

3.5. *Flank wear analysis of the inserts*

As illustrated in Figs. 15 and 16, various forms of wear patterns were observed during machining with the treated insert, including chipping or fracture of the cutting edge, nose wear, abrasion, and chip material adhesion. The micro-hardness and wear resistance of the insert were enhanced as a result of cryogenic treatment followed by repeated tempering. Edge chipping happened as a result of high mechanical stress during milling. Because of the presence of hard materials in the specimen as a result of heat treatment, deep abrasion scars were noticed on the flank face. Plastic deformation was observed on the nasal surface as a result of thermal softening caused by poor thermal conductivity. Because of their tenacity, chip materials stuck to both the rake and flank faces of the insert. Because of this tenacity, wear with a greater depth was noticed at the tool rake face. Deep cryogenic treatment increased micro-hardness, wear resistance, and toughness. As a consequence, as illustrated in Fig. 15(a), (b), 16(a), and 16(b), reduced flank wear with thin abrasion lines was found. The damaged region deteriorated due to lower residual stress concentration and vibration. Furthermore, the effect of chip hammering was significantly reduced due to the decrease in excessive micro-hardness and the increase in wear resistance and toughness. According to the experimental results, deep cryogenic treatment greatly enhanced the micro-hardness and wear resistance of the cutting insert due to the development of η-phase carbide particles. As a result, as illustrated in Fig. 15(a), (b), 16(a), and 16(b), virtually little wear was seen on the flank surface. Furthermore,

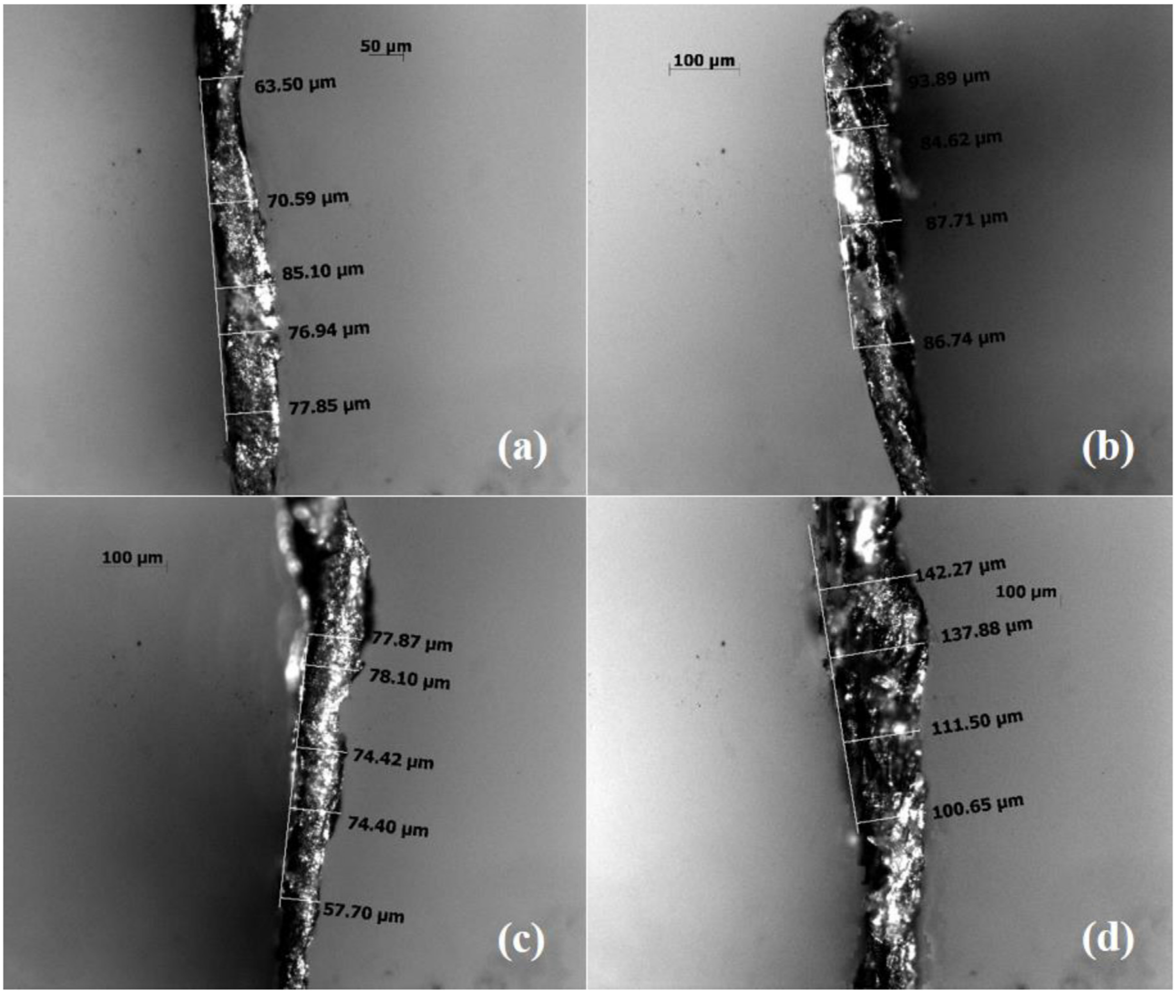

Fig. 18 – Chip thickness obtained during machining using treated cutting insert at feed rate of 0.06 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

thermal fractures, damages, and softening of the cutting edge were not identified due to the increase in heat conductivity. Fig. 15(d) and 16(d) illustrate a damaged region at the main cutting edge caused by the amplification of excessive micro-hardness and brittleness for deep cryogenic treatment during high cutting speed. The compressive residual stress was caused by a large amount of η-phase carbide precipitating along the tool substrate as a result of intense cryogenic treatment. This localised stress concentration may impair tool performance during machining by causing edge fracture. Another cause of the damaged region at the cutting edge was the collision of hard chips with the cutting edge that developed during machining, a process known as chip hammering. Because of the insert's excellent wear resistance and toughness, a smooth wear pattern could be visible at the flank surface, as illustrated in Fig. 15(c) and 16(c). A very small fragmented zone on the rake face was also seen due to improved wear resistance, as was abrasive wear due to strong chip flow on the rake surface, as illustrated in Fig. 15(d) and 16(d). Other wear processes, such as plastic deformation, notch wear, thermal softening, and so on, were not found to be responsible for the increased thermal conductivity, high micro-hardness, and decreased residual stress concentration generated by repeated tempering. Lower cutting speeds and feed rates resulted in less rake surface wear, as seen in Fig. 15(a), (b), 16(a), and 16(b). Hot chips were formed during the continuous turning operation; however, because of the treated insert's high thermal conductivity and superior hot micro-hardness, these hot chips did not harm the rake surface. Because of its excellent wear resistance and augmentation of toughness, the treated insert did not chip or fracture at low cutting speeds. When machining Ti–6Al–4V at high speeds, very high cutting zone temperatures developed, and the cutting tool was subjected to ultrahigh frequency and intense impact thermal mechanical pressures. The workpiece material displayed brittle behaviour at lower cutting speeds, with no impact from strain rate or temperature. Increased cutting speeds result in greater material ductility and higher cutting temperatures.

3.6. *Chip morphology analysis*

Chip morphology is critical in the dry machining of hard alloys. The chip morphology has a significant impact on both

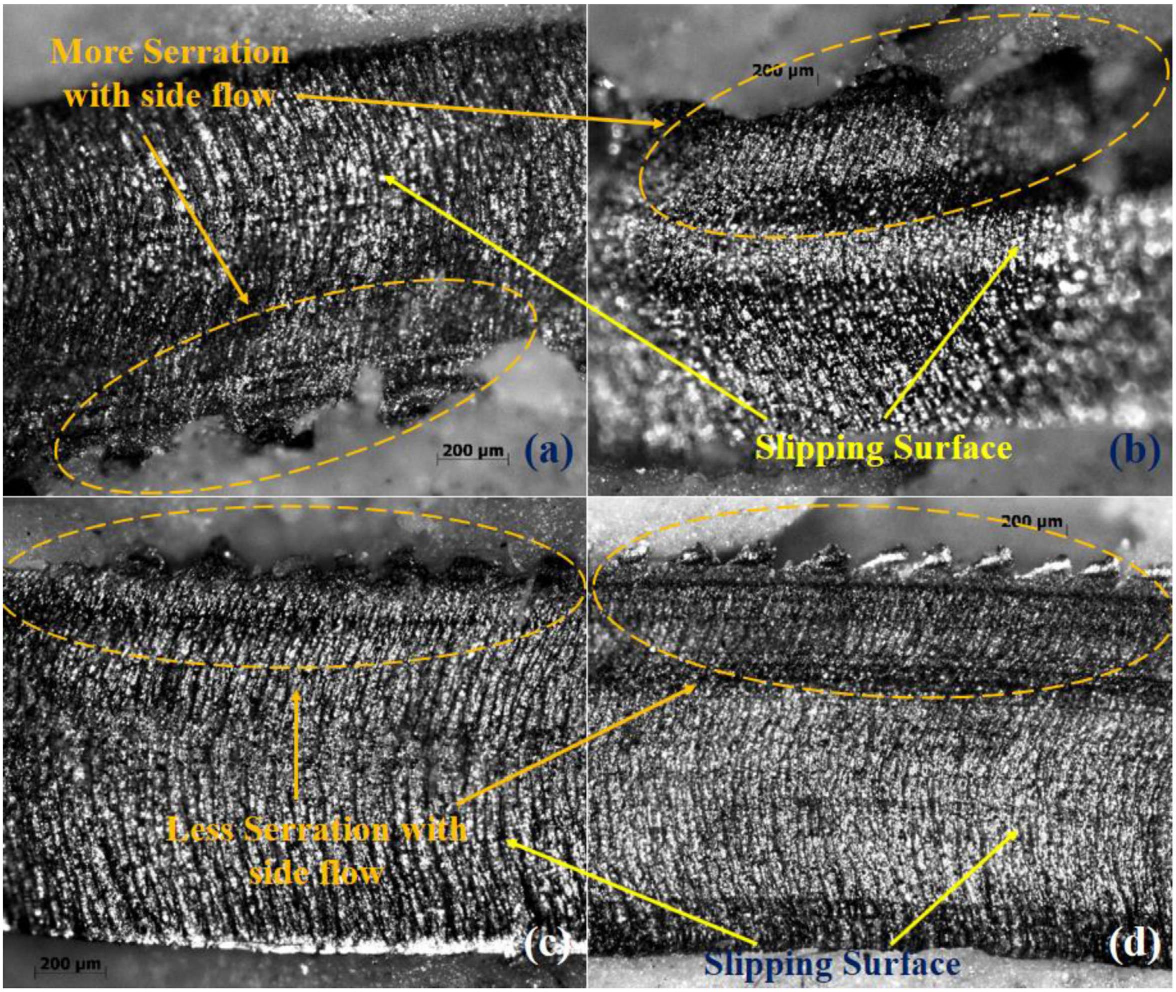

Fig. 19 – Chip lamella obtained during machining using treated cutting insert at feed rate of 0.04 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

surface quality and tool life. The output parameters are influenced by the shape of the chips produced and the manner in which chips come into contact with the tool tip throughout the machining process. Variations in cutting parameters can have an impact on surface quality, heat production, and wear buildup along the cutting edge, all of which have a direct impact on the life of the cutting inserts. When continuous and discontinuous chips are formed at the interface of the rake and flank, they can cause vibrations that damage the surface quality of the machined item and eventually contribute to increased wear. As a result, it is critical to understand the nature of the chip created as well as the chip shape linked to the changing of cutting parameters.

3.6.1. *Chip thickness*

Because the machining was done at a consistent depth of cut, the chip thickness did not change appreciably (see details in Figs. 17 and 18). Micrographs of chips with a maximum thickness of 81 m while the feed rate was 0.04 mm/rev and the cutting speed was 160 m/min are shown in Fig. 17(a)–17(d). Micrographs of chips with a maximum thickness of 142 m while the feed rate was 0.06 mm/rev and the cutting speed was 160 m/min are shown in Fig. 18(a)–18(d). The change in chip form and size as a result of cutting speed In general, tangled helical chips were produced, and the form of the chip stayed nearly constant at varied cutting rates. The discrepancy might be caused by a greater tool wear rate during machining.

3.6.2. *Chip lamella*

Micrographs of chip lamella acquired during machining using a treated cutting insert at feed rates of 0.04 mm/rev and 0.06 mm/rev and varied cutting speeds (73 m/min, 95 m/min, 124 m/min, and 160 m/min) are shown in Figs. 19 and 20. At a high feed rate, the chip became entangled and its structure altered, resulting in a saw tooth impression on the chip surface, which was caused primarily by shear deformation at the primary and secondary shear zones. Furthermore, the increased contact length between the chip and tool induced considerable heat production, causing microstructural

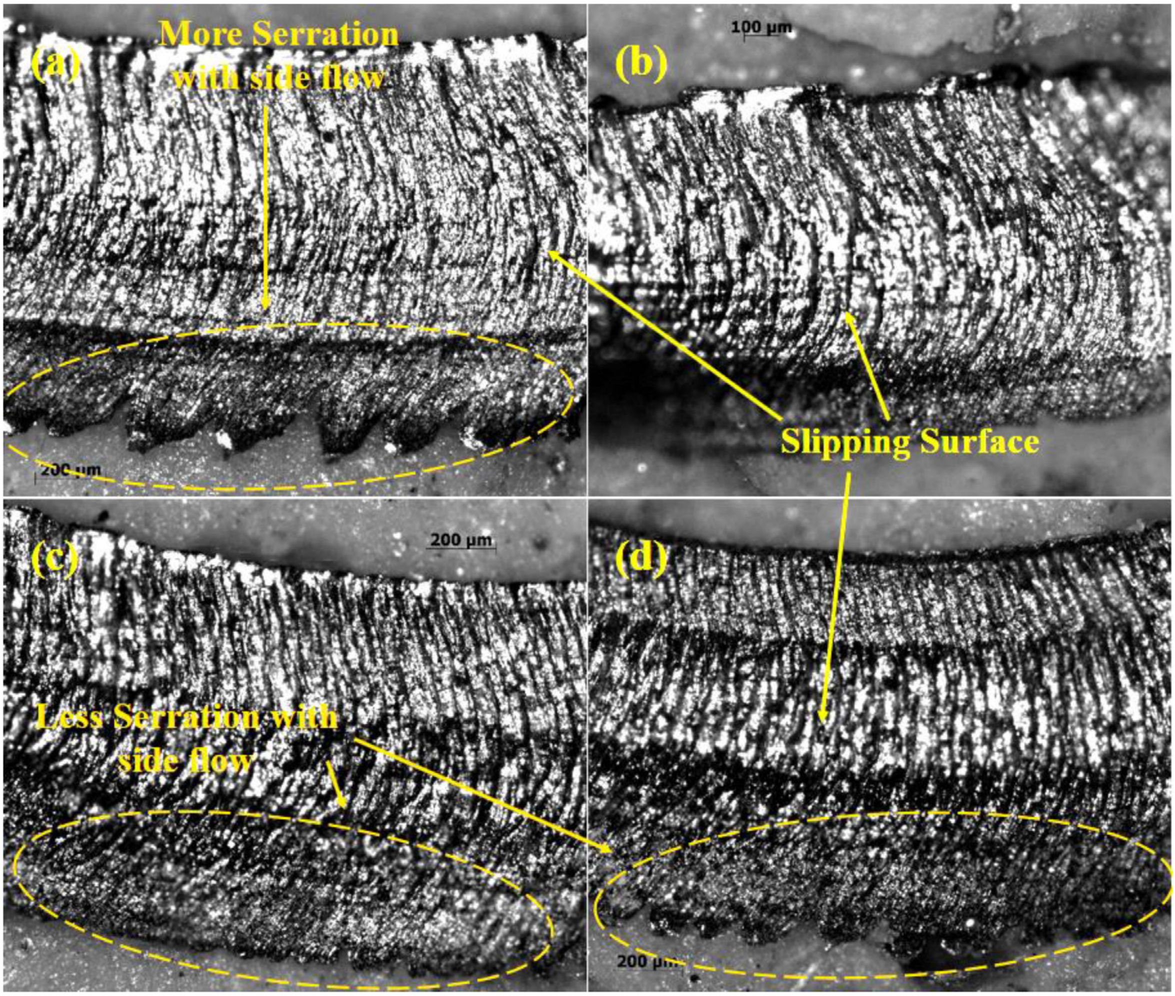

Fig. 20 – Chip lamella obtained during machining using treated cutting insert at feed rate of 0.06 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

changes and thermal deformation. This was the primary cause of the saw-tooth chip's creation. More heat was created as a result of maximal flank wear, which led to a broader saw tooth chip at high cutting speeds, as seen in Fig. 19(d) and 20(d). At lower cutting speeds, the saw-tooth structure was more serrated, whereas at higher cutting speeds, it was less serrated. During this current experimental inquiry, another essential aspect of chip morphology was discovered, known as chip side flow. This might be due to a significant increase in micro-hardness, wear resistance, and toughness for cutting inserts following cryogenic treatment and tempering.

3.6.3. *Chip micro analysis*

Figs. 21 and 22 illustrate serrations and free surfaces of chips created at feed rates of 0.04 mm/rev and 0.06 mm/rev and varied cutting speeds (73 m/min, 95 m/min, 124 m/min, and 160 m/min). Cutting speeds increased chip serrations (see Fig. 21(a)–(d) and 22(a)–(d)). The chip segment creation is inconsistent at lower cutting speeds (73 m/min and 95 m/min), resulting in an irregular height of the individual serrated chip and obvious intermittent shear initiation (see Fig. 21(a), (b), 22(a), and 22(b)). The chip serration was more obvious at 124 m/min, and the chip segment form also has a regular pattern, and the saw tooth profiles are more visible (see Fig. 21(c) and 22(c)). With saw tooth profiles at a cutting speed of 160 m/min, the chip segment formations were exact and compact (see Fig. 21(d) and 22(d)). The segments are more consistently placed and seem denser. Furthermore, the lamellae formed on a chip-free surface get denser as the cutting speed increases. The number of lamellae formed on the chip's free surface increased. This occurs when the intensity of a plastically deformed material increases due to thermal softening processes. The creation of the cutting tool chip occurs when the workpiece approaches it. As a result of the distortion of the segment edge along the shear plane and the compression of the segment length caused by the fracture and plastic strain, distinct chip segment forms arise. The form of the chip segment changes as the cutting speed changes. An uneven form of the chip segment is seen at 73 m/min and 95 m/min (as shown in Fig. 21(a), (b), 22(a), and 22(b)). At 124 m/

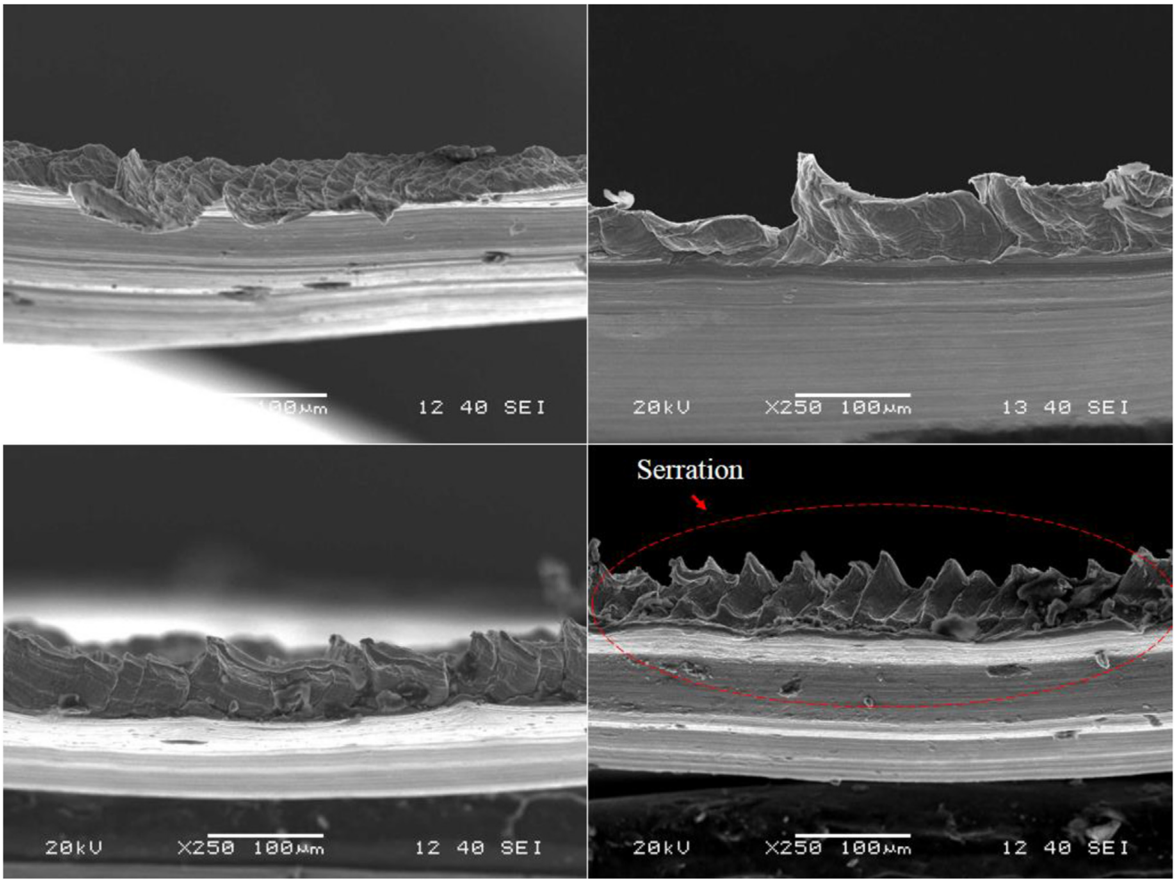

Fig. 21 – Serrations of chips obtained during machining using treated cutting insert at feed rate of 0.04 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

min, the chip segment serration follows a regular pattern, although the chip segments are not in appropriate form (Fig. 21(c) and 22(c)). The serration of the chip segment, as well as the trapezoidal form of the segment, were placed in a regular pattern at 160 m/min (Fig. 21(d) and 22(d)). The chip fragment was generated as a result of fracture and plastic strain (see Fig. 22(a) for details). The presence of shear and normal fracture modes caused some variance in the length of the fracture. High-speed machining causes this form of fracture.

When comparing the machining performance of the treated cutting insert in this study to earlier studies, the convergence of the findings obtained is excellent. When turning with a deep cryo-double-tempered treated KC5010 cutting insert, chip formation thickens as cutting speed and feed rate rise along with flank wear, as observed by Pradhan et al. [17], Maity et al. [29], and Das et al. [35]. They also discovered that when cutting speed increases, chip serration increases and takes on a more uniform shape. Deshpande et al. [33] discovered that cryo-treated cutting inserts outperformed untreated carbide cutting inserts on hard materials such as Inconel 718, with cutting speed and feed rate being the most relevant characteristics. Sreeramareddy et al. [38] reported that by treating the carbide cutting insert in a deep cryogenic environment (below −150 °C), the micro-hardness of the cutting insert was increased, as was the thermal conductivity of the tungsten carbide, resulting in a decrease in tool tip temperature during turning operations, which helped to reduce tool flank wear. Gill et al. [39] showed that deep cryogenic treatment followed by double tempering of the carbide cutting insert improved machinability and reduced flank wear in both dry and wet machining conditions while turning hardened steel compared to an untreated cutting insert. In dry machining settings, Seah et al. [40] and Yong et al. [41] discovered that deep cryogenic treatment followed by tempering of the carbide cutting insert improved machinability and reduced flank wear when compared to an untreated cutting insert. It also increased the insert's micro hardness, which reduced flank wear and enhanced machining at high cutting speeds with a low feed rate. Padmakumar et al. [43] also observed that deep cryogenic treatment followed by tempering of the cemented carbide cutting insert improved machinability and reduced flank wear while turning cast under dry machining conditions when compared to an untreated cutting insert. Furthermore, it increased the micro hardness of the implant, which helped to reduce flank wear.

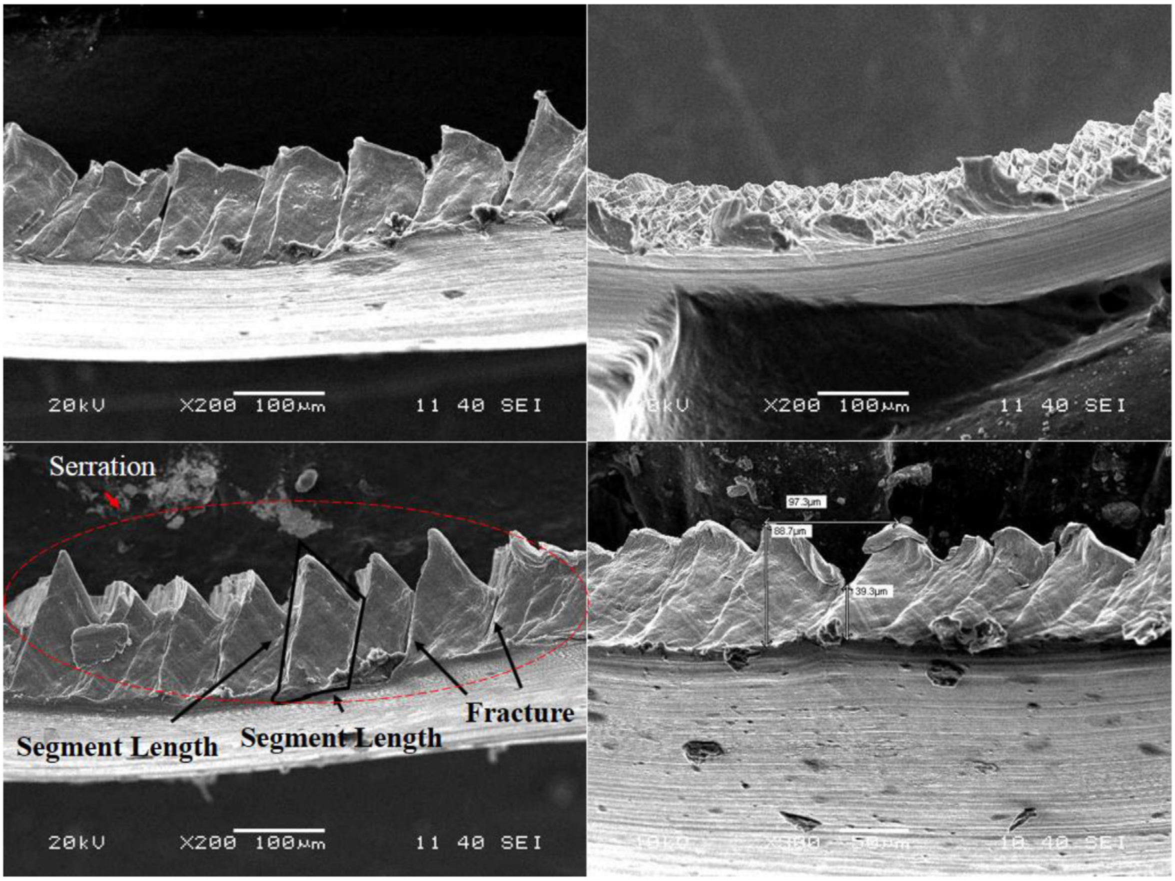

Fig. 22 – Serrations of chips obtained during machining using treated cutting insert at feed rate of 0.06 mm/rev and different cutting speed (a) 73 m/min, (b) 95 m/min, (c) 124 m/min (d) 160 m/min.

4. Conclusions

The current study looked at how machining factors affected dry turning of Ti–6Al–4V alloy with a treated carbide cutting insert (KC5010). Deep cryogenic treatment was employed for cutting insert, followed by double tempering. The effect of the treatments on the cutting inserts was investigated using microstructural investigations. Cutting speed and feed rate at a constant depth of cut were examined for their influence on machining properties (torque, force, tool wear, surface roughness, and temperature). The impact of tool wear, chip thickness, and other variables was discussed. The following significant findings were reached from this work.

- The cryogenic treatment permanently reduces micro-stresses, and the carbide grain size and shape in treated inserts were consistently distributed and homogenous, increasing the cutting tool's endurance.
- As cutting speed increases, all response parameters increase at the same time by more than 300%. When cutting speed increases from 73 m/min to 160 m/min, torque rises from 9.4 Nm to 45.1 Nm, temperature rises from 163 °C to 487 °C, cutting force rises from 136 N to 645 N, tool wear rises from 0.112 mm to 1.692 mm, and surface roughness rises from 0.68 μm to 1.91 μm.
- Deep cryogenic treatment enhanced microhardness, resistance to wear, and toughness. As a result, there was reduced flank wear with tiny abrasion lines. Lower cutting speeds and feed rates resulted in less rake surface wear.
- Because the machining was done at a set depth of cut, the chip thickness did not change much. As chip thickness increased continuously as cutting speed increased, so did the variety of chip form and size as a function of cutting speed.
- At a high feed rate, the chip became entangled and its structure altered, resulting in a sawtooth imprint on the chip surface. Furthermore, the increased contact length between the chip and tool induced considerable heat production, causing microstructural changes and thermal deformation. More heat was created as a result of maximal flank wear, which contributed to a bigger saw tooth chip at high cutting speeds. The saw-tooth structure was more serrated at lower cutting speeds, whereas at higher cutting speeds, it was less serrated.
- Chip serrations grew in size as cutting rates rose. Lower cutting rates cause inconsistent chip segment creation, resulting in an irregular height of each serrated chip and obvious intermittent shear initiation. At a high cutting speed, the chip segment formations were accurate and compact, with saw-tooth patterns. As a result, the form of the sawtooth becomes more distinct and visible.

This opens the door for further exploration of cutting inserts with cryogenic treatment and tempering. A finite element analysis of the cutting insert's performance while turning hard alloys can be simulated. Multiple cryogenic treatments followed by multiple tempering can be done over different coated and uncoated cutting inserts to investigate their durability and machining performance.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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